PLASMA FLOW AT THE MAGNETOPAUSE

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Thesis Director's Signature

Houston, Texas
May, 1968
ABSTRACT
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On January 13 and 14, 1967, an unusual compression of the magnetosphere during an intense magnetic storm caused the magnetopause to pass inside the orbit of the geostationary spin-stabilized satellite ATS-I. At the time of the boundary crossing, the satellite was located at 6.6 earth radii, approximately two hours past the noon meridian on the dusk side. The boundary crossing was marked by rapid magnetic field changes at the satellite position, and anomalously high anisotropic ion fluxes detected by the onboard Rice suprathermal ion detector. The Rice ion detector samples fluxes in the equatorial plane of the earth, in approximately 12° increments. There are 20 differential energy passbands covering 0-50 ev and two integral passbands that sample energies >0 ev and >50 ev. A complete energy spectrum is covered in 112 seconds, while a 360° angular scan is completed in approximately 0.64 seconds.

During the almost one hour the magnetopause was in the satellite's vicinity, several fluctuations in the local magnetic field and ion directional distributions indicated multiple boundary crossing by the ATS-I. In addition to the pure magnetosheath and pure magnetospheric ion flow
patterns, a new component of ion flow was found close to, inside of, and along the magnetospheric boundary. The streaming energy of this flow along the boundary was less than that observed in the magnetosheath, but greater than that observed in the pure magnetosphere. This new component is thought to be the "return" flow (to the tail) for the magnetospheric thermal plasma found to be convecting sunward at points deeper within the magnetosphere.
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INTRODUCTION

Bulk motions of the magnetospheric thermal plasma is a requirement of several models of the magnetosphere. Gold [1959] first introduced the idea of magnetospheric field-line motion separate from the motion of the earth, enabled by the earth's insulating atmosphere. Dungey [1961] noted that the magnetic field carried by the solar wind could merge with the earth's magnetic field, in a manner indicated schematically in Figure 1. After merging, the field lines would be pulled over the polar cap by the solar wind and reconnected in the lee of the earth. This picture implies a return flow of the connected field lines which, in turn, implies bulk motion of the magnetospheric plasma because of the "frozen-in" flux concept, or, equivalently, the particles drift under the influence of a cross-tail electric field given by $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$.

Following Dungey's model of solar wind-magnetosphere interaction, Axford and Hines [1961] explicitly proposed a convective motion of the magnetosphere. It was their view that the convective motion was principally driven by a viscous-like interaction between the solar wind plasma and the magnetospheric plasma. The Axford and Hines' convective flow pattern in the equatorial plane is illustrated in Figure 2.
More recent work by Taylor and Hones [1965], Nishida [1966], Brice [1967], and Kavanagh, et al. [1968] among others have dealt with magnetospheric plasma flow. All of these models agree that the plasma flows from the tail toward the day side of the magnetosphere, except for a forbidden region associated with the plasmasphere. Recent experimental data have confirmed this picture of the plasma flow [Freeman, 1968].

There is some question of the behavior of the plasma near the magnetospheric boundary. Brice's model (Figure 3) shows the plasma streamlines running up to the boundary, while Nishida [1966], Axford and Hines [1961], and Kavanagh, et al. [1968] all show a return flow of the plasma to the magnetospheric tail inside the boundary (Figures 4 and 5).

The experiment apparatus described herein was designed to search for bulk convective motions of the magnetospheric plasma. Placed aboard the ATS-I geostationary satellite, the apparatus, designated the Rice University suprathermal ion detector, detects anisotropies in ion fluxes in the earth's equatorial plane. The ATS-I satellite was launched 6 December 1966 into a nearly circular orbit at 6.6 earth radii ($R_E$) geocentric distance and $0^\circ$ inclination. It is parked approximately over the mid-Pacific at
150° W. longitude. The satellite is spin stabilized at approximately 97 RPM with the spin vector anti-parallel to the earth's rotational vector.

On the 14th of January 1967, the magnetosphere was compressed inside the geostationary orbit. For almost an hour the satellite remained close to the magnetospheric boundary as the boundary moved back and forth across the satellite's orbit. During this period the Rice ion detector provided remarkable data on the substantial and varied ion fluxes in the boundary region. It is the bulk flow of these ions in the vicinity of the magnetopause that is treated herein.
EXPERIMENT APPARATUS

The experiment apparatus consists of a miniature retarding potential analyzer with an 8 mm diameter funnel channel-electron-multiplier as the sensing element. Ion produced pulses from the channel-electron-multiplier are fed to a "difference" counter that is synchronized with a square-wave simultaneously placed on the retarding potential grid. The synchronism phase is such that the "difference" counter adds up or accumulates counts during the negative square-wave excursion and subtracts counts during the positive excursion. Thus at the end of a square-wave cycle the counter contains the net number of counts due to positive ions whose energies lay within the passband ΔE defined by the amplitudes and absolute magnitudes of the positive and negative excursions of the square-wave. These data are referred to as differential energy step or passband data.

At the end of each square-wave cycle the counter is read out through the analog telemetry and then reset with an initial positive bias of 8 counts. Each cycle of up count, down count, readout, and reset requires 20 milliseconds. This cycle is repeated at the same square-wave amplitude (i.e., energy level) 32 times. This requires 640 milliseconds or slightly more than one spin period of the satellite. Each
successive readout provides the directional positive ion flux $12^\circ$ displaced in azimuth from the previous readout. Absolute azimuth reference is obtained by a sun sensor, clock, and counter which measure time from the start of the telemetry sequence to the sun pulse. The detector look-axis is perpendicular to the spin-axis of the satellite which is in turn anti-parallel to the spin-axis of the earth to within $1^\circ$. Thus the detector scans directions in the equatorial plane of the earth. Following each such set of angular distribution flux samples at a given energy (and a 5 second wait to share the telemetry with other experiments), the energy level is advanced to the next step.

Table I gives the energy steps for the instrument. There are twenty differential steps covering the range from 0 to 50 ev in varied size steps. All of the differential energy steps are contiguous. In addition to the twenty differential steps from 0 to 50 ev, there are two integral steps at 0 and 50 ev respectively. The integral steps, during which the counter registers all counts greater than the specified energy, are accomplished by inhibiting the subtract-counts or positive square-wave excursion portion of the data accumulation cycle.

A complete energy spectrum requires 112 seconds. As will be shown, during the magnetopause crossings important variations are observed in the
low energy ion fluxes in time intervals very much less than this. In contrast to the long time required to obtain an energy spectrum, a complete set of angular distribution data is obtained at each energy in 0.640 seconds. This has led to a concentration on determining the directionality of the ion flux rather than the energy spectrum when high time resolution is required. If the fluxes are high it is possible to determine the angular distribution of the majority of ions regardless of what energy step the instrument is on at that time; that is, even if the energy step being measured is not the same as the energy of the ions. This is accomplished by examining the deviations of individual data points (net counts in the difference counter) from the mean of zero. Directions of high background flux show a higher probability density for data points distributed further from the mean. Appendix A explains in detail how the data were treated and what criteria were applied to accept statistically significant anisotropies. The result of this analysis is that flux directionality information is available even if the temporal variations are such that little or no spectral information can be gleaned from the data.

The ion detector data is all accumulated over the first 0.64 seconds after the start of each telemetry sequence. For simplicity the time assigned to each directional flux datum point in the following graphs is
the time of the start of the telemetry sequence. Hence, the time assigned
to these data points is accurate to 0.64 seconds but is always slightly
early. In the graphs we also show data from the ATS-I onboard vector
magnetometer (data generously supplied by W. D. Cummings and P. J.
Coleman, UCLA). There is a 5 second uncertainty in the exact time that
should be attached to the magnetometer data. This arises because the
magnetometer data from which the vector is constructed is accumulated
over a large fraction of the 5.12 second telemetry sequence but the time
assigned to the data is the time at the start of the sequence.

Regarding the sensor itself, the channel-electron-multiplier is held
at 3 KV negative at the ion input end. This -3KV serves the triple
function of post-acceleration of the incoming low energy ions, high voltage
bias for the channel-electron-multiplier operation, and exclusion of incoming
low energy and secondary electrons below 3 kev. Therefore, during the 0
and 50 ev integral energy steps the detector is sensitive to all positive
ions of energy greater than 0 (actually greater than the unknown satellite
potential) and 50 ev, respectively, and electrons of energy greater than
3 Kev.

The detector has a unidirectional geometric factor of \(0.4 \times 10^{-3} \text{ cm}^2\)
stere and a full view angle of 27°. The field of view is circular.
Following a very quiet day geomagnetically (January 12, 1967), a substantial geomagnetic storm developed, starting at approximately 1200 U.T. on January 13 and continuing for over 24 hours. The horizontal components from magnetograms taken at San Juan, Honolulu, and Guam show the storm (Figure 6). At 1200 U.T. on January 13, two impulses occurred representing the sudden commencement of the storm. Some six hours later the main phase of the storm began. The 3 hour $K_p$ index at the time of the sudden commencement was 6 and later rose to 8 shortly after 0000 U.T. on January 14.

Approximately four hours after the beginning of the main phase, there occurred a pronounced worldwide sudden impulse which varied in amplitude from 50 $\gamma$ at Guam to 10 $\gamma$ at San Juan.\footnote{1. $1 \gamma = 10^{-5} \text{ gauss}$} At the time of this sudden impulse the ATS-I was about two hours past the noon meridian moving toward the dusk meridian. The onboard vector magnetometer \cite{Cummings,1968} simultaneously showed a dramatic change in the magnetic field at the satellite, which has been associated with the compression of the magnetosphere to a point inside the ATS-I orbit (6.6 $R_E$).
Following the initial magnetospheric boundary crossing by the ATS-I, the boundary was in the satellite's proximity for approximately an hour, making repeated crossings of the satellite orbit.

At the time of the crossing, the particle fluxes monitored by the Rice ion detector changed energy and flow direction. The repeated boundary crossings allowed enough data to be gathered that a picture of the ion flow on both sides of the boundary could be constructed. The ion observations are divided into distinct categories: (1) observations prior to the first boundary crossing, (2) observations during the first boundary crossing, and (3) observations during subsequent crossings.

I. Observations prior to the first boundary crossing

Most of the time particles monitored by the Rice ion detector are isotropic in directional flow distribution, with almost all of the particles having energies >50 ev. However, shortly after 2305 U.T. on January 13, a very directional flux of ions having energies <50 ev was detected, and persisted except for two brief periods until the boundary crossing shortly before 0008 U.T. on January 14. These particles generally flowed toward a point slightly clockwise from the sun, looking down on the equatorial plane. Figure 7 shows an equatorial polar plot of typical arrival directions of the ions.
The remarkable feature of these ions is their sharp directionality, indicating very little thermal spread. Most of the ions detected were restricted to one or two $12^\circ$ angular sectors in arrival direction. Figure 8 shows a typical energy spectrum measurement, with the peak at $\sim 3$ ev per unit charge.

These low energy, highly directional ions have been observed on two other occasions by the Rice ATS-I ion detector [Freeman, 1968]. They are thought to be evidence of convective motion of the magnetospheric plasma flowing from the magnetospheric tail toward the sunlit side of the magnetopause.

Figure 9 summarizes the flow of the low-energy ions preceding the boundary crossing. Both flow direction and the direction the detector was pointing when the maximum flux was observed are shown. The flow directions, derived from the direction of the detector when the maximum flux was observed, are shown as vectors that represent the instantaneous component of flow in the geographic equatorial plane. In addition, Figure 9 shows a diagrammatic representation of the ATS-I at the time of the boundary encounter. All data in Figure 9 come from the E $> 0$ ev passband; there were no data above background in the E $> 50$ ev passband during this time. Also shown is the z- or horizontal component of the
ATS-I onboard vector magnetometer from data supplied by P. J. Coleman and W. D. Cummings, UCLA. Figure 9 also shows that a few seconds before the magnetopause was encountered, the ion flow abruptly changed direction, to an arrival direction of 100°.

2. The initial encounter with the magnetopause

A few seconds before 0800 U.T. on January 14, the horizontal component of the magnetic field at the ATS-I location changed from $+161\,\gamma$ to $-131\,\gamma$ within 35 seconds. For approximately 1$\frac{1}{2}$ minutes prior to this, the field z-component had increased from a relatively steady $+115\,\gamma$, indicating field compression. These data plus the disappearance of electrons [Lanzerotti, Brown, and Roberts, 1968; Lezniak and Winckler, 1968] and the appearance of energetic, streaming ions indicated a crossing of the magnetopause.

In conjunction with the magnetic field changes, the ion flow directions and energies changed dramatically, as shown in Figure 10.

This and subsequent figures show the horizontal component of the magnetic field at the ATS-I location, the ion direction of flow, and the arrival direction of the peak flux (direction the ion detector was pointing), all plotted as a function of Universal Time. Points plotted as circles with
error bars represent data from the integral energy passbands and are labeled accordingly. The error bars represent full-width-half-maximum values of a smooth curve drawn through the peak. The other points represent differential energy passband data where the length of the bar represents the breadth of the peak, as explained in Appendix A. Flow vectors derived from the differential energy passband represent the direction about which the datum is symmetric.

For approximately one minute following the boundary crossing, the ion flow direction was somewhat unstable, the ions arriving from between $20^\circ$ and $90^\circ$. After approximately 0009 U.T., the flow settled down to directions consistent with the streaming magnetosheath plasma [Bridge, et al., 1965; Wolfe, et al., 1966; and Gosling, et al., 1967].

The spread in the angular distribution of the ion flow and the energy spectrum changed considerably on crossing the magnetopause. Figure 11 shows a polar plot of the ion arrival directions in the equatorial plane. The ions in the magnetosheath have an angular spread covering almost one quadrant. The energy of the ions in the magnetosheath also is much greater than in the magnetosphere, indicating a higher-velocity flow. The data points at 0009:27 and 0009:37 U.T. in Figure 10 were taken with the $E > 50$ ev and $E > 0$ ev integral steps, respectively. The
difference in the flux between these two points is ~11%, indicating the majority of ions in the magnetosheath have energies greater than 50 ev.

Table II gives representative fluxes in the $E > 0$ ev and $E > 50$ ev channels throughout the boundary crossing period. The flux values shown are in the scan plane of the detector and therefore do not include fluxes from above and below the detector. It should be noticed in Table II that the low energy ion flux approximately doubles prior to the boundary crossing.

One should keep in mind in the examination of this and subsequent data that the ATS ion detector is also sensitive to electrons with $E > 3$ kev. The general absence of electrons in the magnetosheath [Lanzerotti, et al., 1968; Lenziak and Winckler, 1968] and the high directionality of the flux leads to the belief that the flux measured is predominately that of ions.

3. Subsequent crossings of the magnetopause

Following the initial boundary crossing, the satellite remained in the magnetosheath for approximately 40 minutes. During this time the ion flow was essentially the same as that shown in Figures 10 and 11. This interval was then followed by 15 minutes of repeated boundary crossings and partial boundary crossings (occasions when the boundary apparently approached the satellite from within the ATS orbit and then withdrew before a full crossing.
was achieved). These times are characterized by rapid changes in the horizontal component of the magnetic field. Four time intervals that contain these rapid changes have been examined in detail for changes in the plasma flow directions.

A. 0024 to 0027 U.T.

The first large change in the magnetic field z-component occurred shortly after 0025 U.T., when the field changed from approximately $-100\gamma$ to $+120\gamma$. Prior to the field reversal the ion flow directions and energies were those of the magnetosheath plasma. At approximately 0026:10 U.T., the field again reversed and, after some oscillations in the neighborhood of $-50\gamma$, returned to the pre-reversal values, as did the ion flow parameters. Figure 12 illustrates the magnetic field z-component and ion flow direction during this period.

With the apparent reentry into the magnetosphere at approximately 0025:15 the flow vector swung approximately $180^\circ$ to a direction pointing slightly clockwise from the sun. Ten seconds later, the ion flow vector begins to rotate in a counter-clockwise sense until it returns, after some small oscillations, to magnetosheath-like flow at 0026:15. The striking feature here is that a directional flow persists, even though the satellite has evidently re-entered the magnetosphere. The points at
0025:35 and 0025:50 even show directions of magnetosheath-like flow! The significance of this will be brought out in the discussion section.

Approximately 15% of the ions have energies < 50 ev before the magnetic field change while approximately 46% have energies < 50 ev after the excursion (see Table II). The first value is consistent with that observed earlier in the magnetosheath.

B. 0041 to 0046 U.T.

During the period 0041 to 0046 U.T. three significant magnetic field changes occurred. Data from the three intervals of field change are shown in Figure 13.

The first period is characterized by a twenty second duration positive swing of the horizontal component from -100 γ to small positive values. The amplitude of this swing is less than the full value required for the magnetosphere field. The field values are those of the magnetosheath before and after this 20 second excursion.

Throughout this period there is an ion flow vector like that in the magnetosheath. Some 37% of the ions have energies < 50 ev in this region, if fluxes from all directions in the equatorial plane are included (see Table II).
The second rapid magnetic field change in this period occurred at approximately 0043:04 U.T. At that time the field horizontal component changed from $-50 \gamma$ to $+30 \gamma$ where it remained until approximately 0043:20. It then increased rapidly to $+180 \gamma$. The intermediate step is similar to that seen two minutes earlier, except the magnetopause subsequently moved on out past the ATS-I, whereas earlier it subsequently receded.

Again, flow along an idealized magnetospheric boundary is present throughout this period. Data taken after 0043:30 showed essentially isotropic flow, indicating full magnetospheric reentry.

The data at 0043:15 and 0043:25 were taken with integral steps. Some 39% of the ions have energies $< 50$ ev, consistent with the value observed two minutes earlier.

Following the interval just described, the H component of the magnetic field falls to a null value where it levels off at 0045:00 U.T. At this time there is no flux in the equatorial plane of ions $< 50$ ev. This region does not represent a neutral point in the magnetic field, however, as the perpendicular component is $38 \gamma$ and $72 \gamma$ at the times the integral data were taken. The absence of ions with $E < 50$ ev is peculiar and unexplained at this time.
With the increase in the field's H-component, the ion flow reappears and the vector rotates in a clockwise sense until the flow is toward a point slightly clockwise from the sun. After this, the ion flow is essentially isotropic, indicating magnetospheric reentry.

C. 0052 to 0056 U.T.

The next period of rapid magnetic field changes occurred from approximately 0052 to 0056 U.T., the data from which are shown in Figure 14. The first field excursion was essentially a square-wave one that lasted 20 seconds. As was the case during previous field changes, a magnetosheath-like flow persisted throughout the period. The data taken during the $E > 0$ ev integral step shows a secondary peak displaced approximately $180^\circ$ from the main peak. The appearance of this peak is unexplained at this time, but may be due to electrons with energies $> 3$ kev. This particular point was taken when the ATS-I was evidently close to the magnetopause, and so may be in a region of boundary-forming currents.

No comparison can be made to the flux of ions $> 50$ ev 10 sec. earlier, because of the difference in magnetic field values at the two times. However, it is evident from Table II that the ion flux decreases inside the magnetopause, as one expects.
The second period of interest is an example of straightforward boundary crossing from the magnetosheath into the magnetosphere. The H-component of the field rises from $-120 \gamma$ within 40 seconds. In the meantime, the ion flux vector rotates clockwise from its magnetosheath position and disappears altogether as the ATS-I goes deeper into the magnetosphere.

D. 0059 to 0103 U.T.

Following the outward motion of the boundary at 0055 U.T., the satellite remained inside the magnetosphere for approximately 5 minutes. As shown in Figure 15, at 0059:50 the magnetopause pushed inward again exposing the satellite once more to the directional magnetosheath plasma.

Comparison of the integral flux values at 0100:09 and 0100:19 shows no ions with $E < 50$ ev. The H-component of the field was $-25 \gamma$ and $-103 \gamma$ when the respective data were taken, however, so no conclusion can be drawn from these flux values. It is peculiar, though, that the ion flux is evidently higher at the $-25 \gamma$ point, but one must note that the $-25 \gamma$ value is an extrapolation between two adjacent data points, as that particular magnetometer reading for the H-component is missing.
At approximately 0101:38 the satellite reenters the magnetosphere, exits again some 12 seconds later, and then reenters the last time at 0102:30. During this period the ion flow is magnetosheath-like except for a brief period around 0102:50 when the flow is first turbulent, coming from no distinct direction, then is toward a point slightly counter-clockwise from the sun. At approximately 0102:27 this pattern is repeated, except the turbulence occurs after the flow vector change in direction.

The $E > 0$ ev flux at 0102:11 is greater than any seen previously (see Table II), and is approximately 30% greater than that of $E > 50$ ev taken some 10 seconds earlier. The $H$-component of the magnetic field differed by 100$\gamma$ between the times the data were taken, however. With the full reentry into the magnetosphere, the ion fluxes became isotropic.

4. **Summary of the observations**

To summarize, at least three types of ion flow patterns consistently appeared during the January 13-14, 1967 geomagnetic storm and the subsequent boundary compression inside the ATS-I geostationary orbit.

A. **The pure magnetosphere**

In this region the primary ion flow consists of very low energy ($\sim 3-5$ ev) particles probably undergoing $\vec{E} \times \vec{B}/B^2$ drift under the influence of a large scale electric field that is across the magnetospheric tail. In a
region away from the magnetopause, the flow is generally toward a point slightly clockwise from the sun. It should be noted that the satellite was in the noon-to-dusk quadrant when these data were taken, some two hours past the noon meridian.

Closer to the magnetopause, the flow vector swings to a position approximately normal to the satellite-sun line, as shown by the last data point in Figure 9. In addition, several data points taken with the differential energy passbands (data in Figure 9 are from the \( E > 0 \) ev passband) exhibit this characteristic, namely those at 0025:14 and 0025:19 in Figure 12, and that at 0055:52 in Figure 14. The general narrowness of these peaks indicate little thermal spread, meaning ions of lower temperature than those seen in the magnetosheath.

B. The pure magnetosheath

Outside the magnetospheric boundary, the primary ion flow consists of high bulk velocity plasma. The flow peaks are generally very broad (see Figure 11). The flow directions are consistent with those reported by other observers of the magnetosheath plasma. The energy spectrum indicates 11-15% of the ions have flow energies < 50 ev. Figures 10 and 12 give the clearest examples of the magnetosheath plasma flow.
C. Flow close to the magnetopause

The ion flow close to and inside the magnetopause is characterized by magnetosheath-like features. It persists in regions marked by positive excursions of the magnetic field H-component, as is illustrated particularly at times around 0025:20 (Figure 12) and 0052:50 (Figure 14). As the satellite crosses the boundary, the flow is sometimes turbulent, coming from no particular direction. On both sides of the boundary, however, the flow is generally in the same direction.
DISCUSSION & CONCLUSIONS

The fortuitous compression of the magnetospheric boundary to a point within the orbit of the ATS-I geostationary satellite on January 14, 1967 has enabled a picture to be constructed of plasma flow in the neighborhood of the magnetopause.

The initial observation of a highly-directional, low-energy ion flow toward the sun is consistent with magnetospheric plasma flow patterns postulated by Axford and Hines [1961], Taylor and Hones [1965], Nishida [1966], Brice [1967], and Kavanagh, Freeman, and Chen [1968]. As pointed out by Freeman [1968], the detection of these low-energy ions is in itself an unusual event, the ions having been detected only on two other occasions. On all three occasions, the satellite was in the noon to dusk quadrant, and the period was during the early main phase of an intense magnetic storm.

This observed low-energy ion flow gives direct experimental evidence of the validity of magnetospheric models employing electric fields that cause the plasma to undergo $\vec{E} \times \vec{B}/B^2$ drift. Both drift velocity and inferred electric field strength compare with calculated values. It is not clear in this instance whether the low energy flow acts as a precursor to
the boundary crossing. For a fuller discussion of this low-energy plasma flow, the reader is referred to the paper by Freeman [1968].

An important point to note is the shift in the low-energy plasma flow direction observed immediately prior to the boundary crossing (see Figures 9 and 10). This is interpreted as evidence of being in a region close to the boundary where the flow is "turning the corner" before returning to the magnetospheric tail along the boundary. It is not possible to say how close the satellite was to the boundary at this point, but it clearly is a small distance compared to the size of the magnetosphere.

Data points at 0025:14, 0025:19 (Figure 12), and 0055:52 (Figure 14) also are probably examples of this flow, having been taken when the ATS-I was slightly inside the magnetopause. In addition, points at 0025:24, 0025:29, 0045:35 (Figure 13), and 0102:32 (Figure 15) may be examples of this low-energy flow.

The persistence of ion flow along the boundary, on both sides of the boundary, is an exceedingly interesting feature. The pure magnetosheath flow observed has been studied and reported previously [Bridge, et al., 1965; Wolfe, et al., 1966; Gosling, et al., 1967] and will not be discussed here. The flow inside and along the boundary has a higher
percentage of ions with energies < 50 ev than in the magnetosheath, as can be seen from the following:

<table>
<thead>
<tr>
<th>Time</th>
<th>Satellite Position</th>
<th>Percentage of Flux with E &lt; 50 ev</th>
</tr>
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<tbody>
<tr>
<td>~0009:27-37</td>
<td>Magnetosheath</td>
<td>11%</td>
</tr>
<tr>
<td>~0024:28-38</td>
<td>Magnetosheath</td>
<td>15%</td>
</tr>
<tr>
<td>~0026:21-31</td>
<td>Boundary (?)</td>
<td>46%</td>
</tr>
<tr>
<td>~0041:22-32</td>
<td>Boundary (?)</td>
<td>37%</td>
</tr>
<tr>
<td>~0043:15-25</td>
<td>Boundary (?)</td>
<td>39%</td>
</tr>
<tr>
<td>~0102:01-11</td>
<td>Boundary (?)</td>
<td>30%</td>
</tr>
</tbody>
</table>

Initially, one might associate the streaming plasma inside the boundary with finite penetration of the energetic streaming magnetosheath ions. This penetration would be expected to be at least as deep as one gyro-radius into the magnetosphere (~50 km). Recently Eviatar and Wolf [1968] have calculated the diffusion rate of magnetosheath plasma into the magnetosphere as a result of VLF noise. They find a diffusion rate of about one gyro-radius per gyro-period for very noisy periods; therefore, substantial penetration may be possible.

However, the magnetosheath plasma as the source of the streaming ions inside the boundary is rejected for the following reasons:
1. It is unlikely the satellite was within a gyro-radius of the boundary for the extended periods the streaming plasma inside the boundary was seen.

2. This leaves unexplained the change in energy of the plasma inside the boundary as cited in the above table.

As an alternative, it is suggested the streaming plasma inside the magnetospheric boundary is the "return" flow to the magnetospheric tail of the low-energy convected plasma seen prior to the boundary crossing. If this "return" flow is confined to a thin layer close to and just inside the magnetopause, the flow velocities (and energies) would be expected to be higher than for sunward flow deeper within the magnetosphere. The return flow would probably not achieve the velocities of the magnetosheath plasma, so one would expect to observe a higher percentage of ions with energies \( < 50 \text{ ev} \) inside the boundary as was the case.

The return flow ions are therefore difficult to distinguish from the magnetosheath ions, the only distinguishing characteristics being a lower kinetic temperature and a higher percentage with energies \( < 50 \text{ ev} \). Without an instrument capable of resolving one or both of these features, one would say that a difference in location exists between the magnetic and plasma magnetospheric boundaries.
Figure 16 illustrates the concept of plasma flow in the magnetopause region as interpreted from the Rice suprathermal ion detector aboard the ATS-I satellite. Low energy (3-5 ev) plasma is convected sunward under the influence of crossed electric and magnetic fields in the magnetosphere. As the plasma approaches the magnetopause, it is turned aside, not being able to cross the equipotential magnetopause, and returns to the tail in a relatively narrow region close to and inside of the boundary.

The magnetosheath plasma streams with higher velocity outside the magnetopause with some penetration of the boundary. The penetration of the magnetosheath ions probably accounts for the varied and sometimes turbulent flow seen as the boundary is crossed (Figures 13 and 15).

With this picture in mind, Figures 12 through 15 can be interpreted as follows:

1. **Figure 12** - The ATS-I is in the pure magnetosheath seeing the magnetosheath plasma. At approximately 0025:10 the boundary pushes rapidly outward past the satellite, so that the convected sunward flow of thermal plasma is seen. Immediately the boundary begins to recede again so that gradually the satellite is immersed into the return flow region.
2. **Figure 13**

Case (i) - The boundary moves just past the satellite, so that it briefly is immersed into the return flow region.

Case (ii) - The boundary moves such that the satellite briefly stays in the return flow region, then quickly expands well past the satellite position.

Case (iii) - It is not clear in this case where the ATS-I is relative to the magnetospheric boundary. The turbulent flow and sunward flow directions may be penetration of magnetosheath plasma into the boundary; the absence of ions having energies $< 50$ ev is unexplained.

3. **Figure 14**

Case (i) - The boundary, after expanding past the ATS-I, settles such that return flow is seen, and then the boundary retreats, leaving the satellite in the magnetosheath.

Case (ii) - A rapid expansion of the boundary past the satellite occurs; plasma "turning the corner" prior to return to the tail is seen briefly.
4. **Figure 15**

Case (i) - A very rapid compression of the magnetosphere occurs; return flow is seen briefly before immersion of the ATS-I into the magnetosheath plasma.

Case (ii) - Rapid variation of the boundary occurs before final expansion leaves the ATS-I deep within the magnetosphere. Ion flow seen is mainly that returning to the tail, with some turbulence from penetrating magnetosheath ions.

Finally, the picture constructed from these data is consistent with magnetospheric models sketched in Figures 4 and 5. No estimate is possible at this time as to the thickness of the return region along the magnetopause, except that it must be relatively small compared to the size of the magnetosphere, being on the order of the size calculated by Kavanagh, Freeman, and Chen [1968].
ACKNOWLEDGEMENTS

The author is particularly indebted to Dr. J. W. Freeman, Jr. for suggesting this research, and providing the data from his suprathermal ion detector for analysis. Special thanks are also given to Dr. Freeman for suggestions in treatment and interpretation of the data.

I am deeply grateful to Drs. W. D. Cummings and P. J. Coleman of UCLA for the high-time-resolution ATS vector magnetometer data. Interpretation of the Rice ion detector data would have been impossible without the magnetometer readings.

Many interesting and helpful discussions with members of the Rice University Space Science Department are acknowledged. In particular, discussions with Drs. A. J. Dessler, L. D. Kavanagh, R. A. Wolf, and Mr. A. Chen were particularly illuminating.

Finally, special thanks are due to my employer, NASA Manned Spacecraft Center, for providing the graduate study leave to do this work. This research was supported in part by NASA Contract NAS 9-9561.
APPENDIX A

STATISTICAL TREATMENT OF THE DATA

Even though most or all of the charged particle energies may lie outside of the ion detector's differential energy passband being sampled at a particular time, it is still possible to determine when the detector is in a region of particle fluxes that are significantly above normal background levels.

It is characteristic of the Rice suprathermal ion detector that quiet-day flux levels with essentially no particles with energies < 50 ev cause a normal distribution of background counts in the differential energy channels. Figure A-1 shows a typical frequency distribution of counts from a two-minute segment of January 19, 1967, which was regarded as a quiet day [Freeman and Maguire, 1967]. The two minute segment was taken at approximately the same U.T. as the boundary crossing on January 14, 1967. The data were examined carefully for variances in angular and energy distribution, but none were found. Accordingly, Figure A-1 represents a sum over all energy passbands between 0 and 50 ev and over all directions. The negative counts on the abcissa are the results of the zero-count bias of 8 counts.

The distribution shown has a mean of 0.1 counts and a standard deviation of 3.4 counts. The slight difference of the mean from zero is
probably due to the few counts due to ions in the energy range being sampled. Each passband considered separately has approximately the same mean and standard deviation. It should be kept in mind that this represents the statistical background of the differential energy passbands on a quiet day with no significant particle flux < 50 ev.

A significant increase in the flux outside the passband energies causes many counts to fall outside these quiet-day statistical values. Figure A-2 shows a frequency distribution from an active period on December 24, 1966 [Freeman and Maguire, 1967]. The distribution is non-normal, but still has a mean of 0.1 and tends to be uniform between abcissa values of -8 and +8 counts. Counts in a sample < -8 and > 8 are added together. As can be seen, the majority of counts fall outside 2 standard deviations for the quiet-day distribution.

Therefore, by noting the deviation of counts from the mean, it is possible to detect enhanced particle fluxes, even though there may be no particles present in the energy range being sampled.

The problem now becomes one of recognition of variances in the data caused by enhanced particle fluxes rather than statistical count variations. This is accomplished by the following steps:
1. The two integral energy passbands, which count all ions with energies above 0 ev and 50 ev, clearly show anisotropies in the angular distribution when counts are plotted as a function of detector look angle. Figure A-3 shows a typical angular distribution of magnetosheath ions. The two integral passbands are sampled every 112 seconds and therefore give indications of regions in which to examine the differential passband data for large variances. If all of the ions have energies < 50 ev, as was the case before the first boundary crossing, energy spectra may be constructed in the usual way. The data treatment outlined here applies only when a large fraction of the ions are above 50 ev in energy.

2. On a quiet day, because of the random nature of the background counts in any differential energy passband, the probability of having + 7 (or more) counts in a sample is ~ 5%. The probability of two successive samples (which amounts to two adjacent 12° angular sector scans) having + 7 (or more) counts is the product of the two individual probabilities, or < 1%.

3. The absolute value of the deviation of a sample count from an assumed mean of zero was plotted as a function of detector look
angle for the differential energy passband data. By the above argument, one might expect an indication of enhanced fluxes whenever two adjacent 12° sectors had 7 or more counts. In actuality, anisotropic flux peaks are generally much broader than 24° in the neighborhood of the magnetopause as can be seen from examination of the integral flux data. Therefore, the rare statistical deviation of successive counts outside of 2σ can be identified because of the lack of large count variances in the neighborhood.

4. After plotting the differential passband data, enhanced flux regions were identified by their large variances from zero as a function of angle. Whenever a substantial number of counts within an interpreted peak was < 7, the mean deviation $\sum |x_i - \bar{x}| / n$ was calculated, and required to be > 7 over the width of the peak.

5. It is recognized that the application of counting data gathered during a quiet period to a non-quiet day is not a statistically valid procedure; i.e., probabilities cannot be calculated for counts in a sample to lie outside of ± 7 counts. Application of the criteria described in the paragraphs above to recognize significant directions of enhanced ion flow assumes that the ion
flux in the directions away from the enhanced flow is the same as for a quiet day. Although one might suspect this from examination of the integral passband data, proof of it is outside the scope of this paper.

However, the consistency of ion flow directions derived from the differential passband data with those data from the integral passbands gives strong confidence in the validity of arguments presented. For instance, Figures A-4 and A-5 show a comparison of differential and integral data taken 5.12 seconds apart. Note that these data were taken inside the magnetopause (see Figure 14). The peak in the integral data is obvious. The smaller peak, displaced $\sim 180^\circ$, may be statistical, or due to electrons with $E > 3$ kev.

By the above criteria, the peak in the differential data is identified as being located between $\sim 6^\circ$ and $\sim 126^\circ$. Note also that the peak width is approximately the same in the two figures. The points with arrows are those having $-8$ counts, the negative counting limit. The deviation from zero may actually be larger. A further check was made on the data to test the ability to recognize flow directions. Regression coefficients were calculated between
successive differential points that indicated rather strong flow directions. The coefficients were calculated for different degrees of phase lag; i.e., data from the same angles were matched up and the regression coefficient calculated, then the data from one passband was shifted 12° and the coefficient recalculated, and so on.

As an example, coefficients calculated between points at 0053:03 and 0053:13 varied from +0.704 to -0.274. The highest correlation occurred when the data were displaced by 12°. Since ion flow peaks were interpreted as coming from approximately the same direction by the above outlined criteria, one would expect the highest correlation for small phase lag, as is the case.
APPENDIX B

CALCULATION OF INTEGRAL FLUX VALUES

The data from the integral energy passbands come in the form of $N_j$ counts per accumulation interval. An accumulation interval is that portion of the 20 millisecond up count, down count, readout, reset cycle when the counter is accumulating counts or 2.5 milliseconds. Therefore conversion of the data to counts per second requires division of $N_j$ by $2.5 \times 10^{-3}$ seconds.

The ion detector has a solid angle of sensitivity of 0.0364 steradians and a unidirectional geometric factor of $\sim 4 \times 10^{-4}$ cm$^2$·ster. Unidirectional flux is calculated by dividing $N$ by the product of the accumulation interval and the geometric factor, i.e.,

$$i_j \text{ (ions/cm}^2\text{-sec-ster)} = \frac{N_j}{2.5 \times 10^{-3}}[4 \times 10^{-4}]$$

The detector's solid angle of sensitivity corresponds to a cone having an opening angle of $\sim 12^\circ$, which was verified by calibrations. During the 20 millisecond cycle the satellite spins a fraction less than $12^\circ$, so there is no appreciable overlap of viewing angles from one cycle to the next ($<2\%$). This particular geometry makes it convenient to calculate the total flux in the scan plane of the detector by summing the unidirectional flux accumulated in each $12^\circ$ increment and multiplying by the detector solid angle, i.e.,
If one does not wish to calculate the unidirectional flux, the equivalent form

\[ J = \frac{0.364}{2.5 \times 10^{-3} \times 4 \times 10^{-4}} \sum_{i=1}^{30} N_i \]

may be used. This is the same thing as dividing \( N_i \) by an "omnidirectional" geometric factor, permissible in this case because of the coincidence of the detector solid angle with the rotation angle of the satellite during a counting cycle.
<table>
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<th>Step No.</th>
<th>Passband (ev)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>1</td>
<td>0.25 &lt; E &lt; 0.75</td>
</tr>
<tr>
<td>2</td>
<td>0.75 &lt; E &lt; 1.25</td>
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</tr>
<tr>
<td>16</td>
<td>10.00 &lt; E &lt; 20.00</td>
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<td>Step No.</td>
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<td>---------</td>
<td>------------------------</td>
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<td>20.00 &lt; E &lt; 30.00</td>
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<tr>
<td>19</td>
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<td>20</td>
<td>50 &lt; E</td>
</tr>
<tr>
<td>21</td>
<td>0 &lt; E &lt; 0.25</td>
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</table>
TABLE II

REPRESENTATIVE FLUX VALUES OF $E > 0$ ev and $E > 50$ ev

Flux values have been summed over the observed arrival directions and therefore do not include fluxes from above and below the detector scan plane.

<table>
<thead>
<tr>
<th>U.T.</th>
<th>Max Flux Arrival Dir.</th>
<th>Flux $&gt; 0$ ev cm$^{-2}$ sec$^{-1}$</th>
<th>Flux $&gt; 50$ ev cm$^{-2}$ sec$^{-1}$</th>
<th>H (gammas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2305 - 46.950</td>
<td>220°</td>
<td>3.3 (10$^6$)</td>
<td>Background</td>
<td>+118</td>
</tr>
<tr>
<td>2328 - 18.792</td>
<td>200°</td>
<td>4.9 (10$^6$)</td>
<td></td>
<td>+129</td>
</tr>
<tr>
<td>0003 - 59.211</td>
<td>205°</td>
<td>4.9 (10$^6$)</td>
<td></td>
<td>+118</td>
</tr>
<tr>
<td>0007 - 44.518</td>
<td>100°</td>
<td>9.5 (10$^6$)</td>
<td></td>
<td>+161</td>
</tr>
<tr>
<td>0009 - 26.930 - 37.171</td>
<td>60°</td>
<td></td>
<td>2.5 (10$^7$)</td>
<td>-148</td>
</tr>
<tr>
<td>0024 - 28.176 - 38.418</td>
<td>50°</td>
<td>2.8 (10$^7$)</td>
<td>2.8 (10$^7$)</td>
<td>-119</td>
</tr>
<tr>
<td>0026 - 20.830 - 31.071</td>
<td>70°</td>
<td>3.3 (10$^7$)</td>
<td>1.9 (10$^7$)</td>
<td>-61</td>
</tr>
<tr>
<td>0041 - 22.058 - 32.299</td>
<td>70°</td>
<td>3.5 (10$^7$)</td>
<td>1.9 (10$^7$)</td>
<td>+22</td>
</tr>
<tr>
<td>0043 - 14.712 - 24.953</td>
<td>90°</td>
<td>2.3 (10$^7$)</td>
<td>1.4 (10$^7$)</td>
<td>+28</td>
</tr>
<tr>
<td>U.T.</td>
<td>Max Flux Arrival Dir.</td>
<td>Flux &gt; 0 ev cm(^{-2}) sec(^{-1})</td>
<td>Flux &gt; 50 ev cm(^{-2}) sec(^{-1})</td>
<td>H (gammas)</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------</td>
<td>--------------------------------------</td>
<td>--------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>0045 - 07.365</td>
<td>60°</td>
<td>3.7 ((10^7))</td>
<td></td>
<td>+1</td>
</tr>
<tr>
<td>0052 - 37.979</td>
<td>70°</td>
<td>2.6 ((10^6))</td>
<td></td>
<td>+19</td>
</tr>
<tr>
<td>0100 - 08.593</td>
<td>50°</td>
<td>2.6 ((10^7))</td>
<td></td>
<td>-25</td>
</tr>
<tr>
<td>0102 - 01.247</td>
<td>60°</td>
<td>3.3 ((10^7))</td>
<td></td>
<td>+152</td>
</tr>
</tbody>
</table>
REFERENCES


CAPTIONS FOR FIGURES

FIGURE 1 - Dungey's model of merging of the interplanetary magnetic field with that of the earth and subsequent field-line flow.

FIGURE 2 - Axford and Hines' model showing convective motion in the equatorial plane of the earth's magnetosphere. The convective motion arises from viscous interaction between the solar wind and magnetosphere.

FIGURE 3 - Brice's model of the magnetosphere showing various equipotentials. Plasma (or field-line) flow is along these equipotentials. The effect of the earth's rotation is not shown.

FIGURE 4 - Nishida's model of plasma flow in the magnetosphere. In this model, effects of the earth's rotation are considered.

FIGURE 5 - Magnetospheric plasma flow as calculated by Kavanagh, Freeman, and Chen. The authors do not actually compute a return flow, but imply it from results of the ATS-I data, among others.

FIGURE 6 - Horizontal components from three low latitude magnetograms, San Juan, Honolulu, and Guam, taken on January 13 and 14, 1967. Note the "square-wave" sudden impulses around noon on the 13th signifying the storm's sudden commencement, and the sudden impulse shortly after midnight at the time of the ATS boundary crossing.
FIGURE 7 - A polar plot showing the arrival directions in the equatorial plane of the low-energy ion flux detected for approximately one hour prior to the boundary crossing. These ions generally flowed in a sunward direction with a very sharply peaked angular distribution. These ion fluxes probably result from $\vec{E} \times \vec{B}/B^2$ drift motion of magnetospheric thermal plasma.

FIGURE 8 - A differential energy spectrum of the low-energy ion fluxes detected in the magnetosphere.

FIGURE 9 - An illustration of the low-energy ion flow prior to the first ATS boundary crossing. The horizontal component of the ATS magnetometer is also shown for comparison. Note the last datum point showing a shift in flow direction a few seconds before the boundary crossing. This may be an indication of a return flow of the magnetospheric plasma along the boundary.

FIGURE 10 - The flow directions of the high-velocity plasma outside the magnetospheric boundary. Note that the flow is from $\sim 20^\circ$ to $\sim 90^\circ$ clockwise of sunward. The breadth of the flow directions may be estimated from the error bars on the data points which represent the approximate width of the peak for the differential energy passbands, and the approximate half maximum value of the integral energy passband.
peak. The first datum point is reproduced from Figure 9 showing the low-energy ion flow prior to the boundary crossing. The points labeled $E > 50$ ev and $E > 0$ ev represent integral step data points, as they do in subsequent figures. All other data points are from the differential energy steps.

FIGURE 11 - A polar plot showing the arrival directions in the equatorial plane of ions outside the magnetopause. Note that the flux now comes from clockwise of sunward and has a broad angular distribution. A large fraction of the ions have energies per unit charge $>50$ ev.

FIGURE 12 - An example of temporary penetration of the ATS into the magnetospheric boundary. Note particularly fluxes seen for approximately 40 sec. while in the boundary. The magnetosheath-like component may represent high velocity return flow of the magnetospheric thermal plasma to the tail; the first four points after the boundary crossing probably represent convected magnetospheric plasma before it is turned aside for return along the boundary.

FIGURE 13 - An example of ion flow during multiple boundary crossings. All of the flow observed is probably in the return flow region. The turbulent and sunward flow may be examples of penetration of the boundary by the magnetosheath plasma.
FIGURE 14 - Another example of multiple boundary crossings. The last data point is taken to represent further evidence of the magnetospheric plasma "turning the corner".

FIGURE 15 - The last multiple boundary crossing prior to full reentry of the ATS into the magnetosphere.

FIGURE 16 - A diagrammatic representation of my concept of plasma flow in the equatorial plane in the vicinity of the magnetopause. The low-velocity magnetospheric plasma, flowing because of $\vec{E} \times \vec{B}/B^2$ drift, is turned around inside the boundary and returns to the tail. The flow to the tail is high-velocity due to confinement of the flow to a thin layer just inside the magnetopause.

FIGURE A-I - The quiet-day frequency distribution for a differential energy step. The negative counts are due to the zero-count bias of eight counts per accumulation interval.

FIGURE A-2 - A differential energy step frequency distribution for an active period. Essentially all of the ions have energies above the energy step being sampled. All counts $\leq 8$ are accumulated in the $-8$ level; counts $\geq 8$ have been put into the $+8$ level for symmetry. It will be noticed the mean is still around 0 but the distribution is definitely non-normal.
FIGURE A-3 - An example of anisotropic ion flow detected while the satellite was in the magnetosheath. The data are from the $E > 0$ ev integral energy passband.

FIGURE A-4 - An example of anisotropic ion flow detected while the satellite was close to and inside the magnetopause. The data are from the $E > 0$ ev integral energy passband.

FIGURE A-5 - A plot of differential energy passband data taken 10 seconds later than the data shown in Figure A-3. The arrows indicate counts of -8 in an accumulation interval, the limit on negative counts. In actuality, the difference of the counts from zero may be larger than indicated.
LINE OF FORCE

DIRECTION OF FLOW

FIG 1
FIG 4

SOLAR WIND

MAGNETOSPHERIC TAIL

PLASMAPAUSE

TURBULENT REGION
TIME: \(23 \text{UT} \pm 0.5\) UT
JAN 13 1967

COUNTS/ACCUMULATION INTERVAL

TO SUN

0°

270°

90°

E < 50 ev

J = 6.4 \times 10^7 \text{ ions/cm}^2 \text{ sr sec}

J = 4 \times 10^7 \text{ ions/cm}^2 \text{ sr sec}

FIG 7
POSITIVE ION FLUX (IONS/cm²-SR-SEC-ev)

ENERGY PER UNIT CHARGE (ev)

TIME: ~2332-2334 UT
JAN 13, 1967

DATA POINT MISSING

BACKGROUND LEVEL

FIG 8
ARRIVAL DIRECTION OF MAXIMUM FLUX

UNIVERSAL TIME

FIG 9
FIG. 10

MAGNETIC BOUNDARY CROSSING

FLOW DIRECTIONS

ARRIVAL DIRECTION OF MAXIMUM FLUX

H (γ)

TO SUN

0007 0008 0009 0010
0007 0008 0009 0010

UNIVERSAL TIME

E ≤ 50 ev
E > 50 ev
+IONS
ARRIVAL DIRECTION OF H\(_{\gamma}\)
ARRIVAL DIRECTION OF MAXIMUM FLUX

H (γ)

TO SUN

FLOW DIRECTIONS

ARRIVAL DIRECTION OF MAXIMUM FLUX

0041 0043 0045

UNIVERSAL TIME

FIG 13
ARRIVAL DIRECTION OF MAXIMUM FLUX

H(γ)

TO SUN

FLOW DIRECTIONS

ARRIVAL DIRECTION OF MAXIMUM FLUX

E>50 ev

E>0 ev

UNIVERSAL TIME

FIG 14
ARRIVAL DIRECTION OF MAXIMUM FLUX

FLOW DIRECTIONS

H (γ)

TO SUN

ARRIVAL DIRECTION OF MAXIMUM FLUX

E > 50 ev
E > 0 ev
TURBULENT
TURBULENT
TURBULENT
ISOTROPIC

UNIVERSAL TIME

FIG 15
TO SUN

MAGNETOSHEATH PLASMA

TO THE SUB-SOLAR POINT

MAGNETOPAUSE

HIGH VELOCITY FLOW TO THE TAIL

LOW VELOCITY FLOW (MAGNETOSPHERIC THERMAL PLASMA)

FIG 16
Counts in a Sample

FREQUENCY OF OCCURRENCE

NORMAL DISTRIBUTION CURVE

COUNTS IN A SAMPLE

MEAN $\sim 0.1$

$\sigma \sim 3.4$

FIG A-1
0052:53.341 UT DIFFERENTIAL PASSBAND

MEAN DEVIATION OF PEAK ~ 7.6

Accumulation Interval From Quiet-Day Mean

Absolute Difference of Counts Per

Arrival Direction

Fig. A-5